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HURRICANE HEAT POTENTIAL OF THE GULF MEXICO

by

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THESIS

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Hurricane Heat Potential of the Gulf of Mexico

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

An analysis of the "hurricane heat potential" of the Gulf of Mexico early in the hurricane seasons for the individual years 1965 to 1968 was conducted. Results show that if the heat content of water at 26C is taken as zero, then the amount of heat available per cm^2 in the Gulf varies from approximately 700 to 31,600 calories. The areas of high heat content are found to vary yearly. Further, since the sea surface temperature decrease during a storm depends upon the near surface vertical temperature gradient, the temperature differences between the surface and 30m depth were also studied. Vertical temperature differences were found to vary from 0C to 11.6C, depending upon location. Computations based on ranges of heat content and vertical temperature structure showed that a passing hurricane with an assumed flux from the sea of 4,000 cal/cm^2/day would cause the sea surface temperature to decrease some 3.1C per day in some regions but only 0.8C in others.

STGRADUATE SCHOOL
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I. INTRODUCTION

A. LITERATURE REVIEW

The interaction between the ocean and atmosphere plays an important role in the formation and intensity of hurricanes. Hurricanes are known to form only during portions of the year and over those ocean areas where the sea surface temperatures are normally high and to dissipate rapidly over land. Malkus [1], compares a hurricane to a thermal engine and concludes a large oceanic input in the form of sensible and latent heat is necessary to establish and maintain the pressure gradients which in turn produce and maintain the tremendous winds. It appears then, that the availability as well as the rate of transfer of heat and moisture from the ocean to a hurricane is essential in determining its growth and maintenance.

Numerous studies suggest a relationship between the intensity and paths of hurricanes and the surface and near surface oceanographic temperature structure. Perhaps one of the first efforts to relate hurricane tracks with the sea surface temperature field was that of Fisher [2]. Fisher used average daily sea surface temperature fields from data compiled from merchant ship weather observations. The results indicated a possibility that hurricanes tend to track along areas of warmest water and that they tend to weaken as they move over markedly colder water. Miller [3], also used daily maps in his investigation and suggested that water temperature may be related to the maximum intensity which can be realized in individual hurricanes. Using a large number of 5-day and 10-day period mean values of parameters from

ship weather and sea temperature observations, during hurricane seasons of several years, Tisdale and Clapp [4], found some evidence of consistency in hurricanes tracking along axes of maximum positive sea surface temperature anomaly.

Other studies have been made to determine the effect of tropical cyclones on the water structure over which they pass. Jordan [5] in an attempt to determine ocean temperature changes associated with typhoons, used routine ship observations made before, during and following individual typhoons. He found evidence of cooling of large areas in the wakes of intense storms. The cooling, it was suggested, was related to the initial vertical temperature distribution in the ocean as well as to the strength and size of the storm. Stevenson and Armstrong [6], reporting on shallow water conditions associated with hurricane Carla (1961), found that the influence of the hurricane was not restricted to the surface layers, as there was apparent upward transport of heat from some considerable depth.

The understanding of hurricane behavior and its effect on the ocean is significantly limited by a general deficiency in associated synoptic observations and analyses of the ocean temperature structure. The first systematic observations taken immediately after an intense hurricane, were those of Leipper [7]. He found evidence of upwelling of cold water along the path of hurricane Hilda (1964) and an associated decrease in the sea surface temperature of greater than 5C over a large area. There were also indications that warm surface layers were transported outward from the hurricane center. These layers were cooled and mixed as they moved and downwelling occurred where the waters converged

outside of the central storm area. It is apparent that Hilda not only removed large quantities of heat from the ocean but caused a redistribution of the remaining heat as well. With this redistribution of heat in the ocean the rate of heat transfer processes to the atmosphere, in the area of storm influence, might well be expected to change.

Perlroth [8], used synoptic sea surface weather reports, from ships of opportunity, in an attempt to determine if any relationship existed between hurricane intensity and behavior and the thermal structure of the water masses over which the hurricane passes. His results, which apply to hurricanes which retain their tropical characteristics throughout the life cycle, showed that hurricanes seem to intensify over warm water and to weaken over cool water. From the observed intensification of hurricanes when they passed over the Gulf Stream, he concluded hurricanes react spontaneously in the form of an intensity change when a significant change occurs in the sea surface or near surface temperature structure over which they pass.

Numerous mathematical models have been used to describe the formation, growth and intensification of hurricanes. A common assumption used in the models is that of a constant sea surface temperature. This assumption fails to account for any variability in the water temperature from location to location and precludes any inclusion of the magnitude of heat available in the ocean for transfer to a hurricane as a result of the vertical temperature structure. Since a hurricane takes heat from the ocean, the variability of water temperature structure both in the horizontal and in the vertical must be considered. The above assumption of constant sea surface temperature is not realistic.

Ooyama [9], in a recent model, considers sea surface temperature as an external parameter, spatially uniform over the area of interest, and does not allow for any vertical temperature gradient in the ocean. Results of a case varying the sea surface temperature parameter are interesting as they show the theoretical effect of sea surface temperature change on hurricane intensity. Using an initial temperature of 25.6C, he found that his model barely reached hurricane intensity and that the process took nearly twice as long as when an initial temperature of 27.5C was used. Another case revealed a rapid increase in hurricane intensity resulting from raising the temperature from 25.6C to 27.5C. The reverse effect occurred on a lowering of the sea surface temperature from 27.5C to 25.6C. These mathematical models show a definite relationship between the intensity of a hurricane and the ocean temperature. In these studies the sea surface temperature, once varied, was held constant for the remainder of the computations and the rate of heat exchange was assumed constant throughout. Since heat is removed from the sea, a corresponding decrease in sea water temperature must occur. Thus the results of the model study cannot correspond precisely to what actually would be observed.

Finally, it is interesting to note the results of a recent study by Perlroth [10], where an attempt was made to determine the relationship between tropical storms which reach hurricane intensity and the corresponding mean vertical temperature structure. Data consisted of a historical analysis of monthly mean temperature gradients in the Equatorial Atlantic from the surface to 200 feet. The results indicated favorable and unfavorable mean "potentials" in the ocean for the intensification of tropical storms to hurricanes. Of all the tropical storms that

reached hurricane intensity during the period 1901-1965, he found that approximately 90 percent reached hurricane intensity over areas where the average (64 year) vertical temperature difference between the surface and 200 feet was 3.9C or less and that only 4 percent reached hurricane intensity when the gradient exceeded 8.4C.

Most of the observational studies cited above used averaged sea surface temperatures or averaged vertical temperature gradient data. The result is a tendency to mask the real complexity of the temperature patterns that may exist in the synoptic oceanographic environment. Rough repetitive synoptic oceanographic temperature distribution data, such as those of Leipper [11, 12 and 13] in the Gulf of Mexico, serve to indicate, more exactly, the true nature of the surface and near surface temperature structure.

The studies referenced in the previous pages seem to indicate that a knowledge of the sea surface or near surface temperature distribution alone is not sufficient to indicate the possible intensity or path of a hurricane. A detailed knowledge of the vertical temperature profile is needed in determining the energy in the ocean available for transfer to a tropical storm. A vertical temperature structure that shows a large gradient would have, for a given sea surface temperature, less heat available for transfer than a deep mixed layer structure. A shallow thermocline might represent a water mass profile that would have only small potential for hurricane intensification. Further, a shallow thermocline structure would more readily permit cooling of the sea surface following the passage of a hurricane due to the upwelling. Should the reduced surface temperature persist for any length of time, it could serve as a deterrent to a subsequent tropical storm and possibly

prevent it from intensifying. If a hurricane is truly affected by the underlying sea surface temperature, then those hurricanes which are bringing cold water to the surface could not remain stationary without weakening.

B. OBJECTIVE

The objective of this thesis is to analyze the "hurricane heat potential" in the Gulf of Mexico early in the hurricane season for the individual years 1965 to 1968. An attempt is made to determine, from available data, the magnitude and the distribution of heat available to a hurricane during the month of August in the Gulf of Mexico, for successive years. Further, an effort is made to indicate the variability in the amount and distribution of heat from year to year and to indicate for some sample cases the magnitude of the sea surface temperature decrease which might result from the passage of a hurricane.

II. APPROACH

A. GENERAL

In most cases, too few recurring synoptic observations are made in an area to enable an accurate or complete indication of a parameter and its annual variation. Perhaps unique to a given area are certain hydrographic cruises conducted in the Gulf of Mexico from 1965 to 1968 [Leipper, 11]. These were conducted through the Texas A&M Research Foundation, on the University's research vessel R/V ALAMINOS. The cruises were planned in an effort to obtain synoptic information on the temperature-depth structure in the Gulf of Mexico. The periods of the cruises were in early spring and in late summer, to obtain information during the coldest and warmest periods of the year. Through the study of the thermal structure an indication of the circulation in the eastern and central Gulf of Mexico was obtained and the repetitive nature of the cruises enabled a comparison to be made between years and seasons.

Leipper [20], presented the sequence of the current patterns, as indicated by the topographies of 22C isothermal surfaces. Figures 2, 4, 6 and 8, show the results for various August periods and indicate the year to year variation in the loop current. They also provide an indication of the available heat in this area of the ocean. Obviously, for a given initial surface temperature, there is for example, more available heat where the 22C isotherm is found at 250m than where it is found at 50m.

Some definitions are required:

(1) Hurricane heat potential: This refers to the excess ocean heat content over that contained in 26C water. This is sometimes abbreviated as heat potential or heat excess.

(2) Selected volume: This represents a column of water overlaid by a unit surface area and it is used in heat calculations.

(3) Deep eastern Gulf region: This is an area loosely defined in the Gulf of Mexico, enclosed by latitudes 23.5N to 27.5N and longitudes 86W to 89.5W.

The availability of the temperature-depth structure information for consecutive years, early in the hurricane season, provides a unique opportunity for the analysis of available heat potential and for comparisons on a year to year basis.

B. DATA SOURCES

For the purposes of this analysis the synoptic data gathered from four cruises were used. Data were obtained using standard Nansen casts, bathythermograph and a salinity-temperature-depth recorder (STD). The last first became available during the 1966 cruise. Table I indicates the inclusive dates of the cruises, the information sources and the number of samples from the various sources taken during each cruise.

TABLE I - Data Sources

Cruise No.	Inclusive Dates	BT's	Nansen Casts	STD's
65-A-11	10-24 Aug 1965	309	30	--
66-A-11	4-18 Aug 1966	172	11	94
67-A-6	4-22 Aug 1967	265	31	112
68-A-8	17 Aug-5 Sep 1968	304	22	68

The Nansen cast and STD data were tabulated for the actual sample depth and for the values interpolated to standard depths in the various reports by Leipper [11, 12 and 13]. The bathythermographic data tabulated for every five meter depth interval were obtained from the National Oceanographic Data Center.

C. VERTICAL TEMPERATURE DIFFERENCE, 0-30m

To obtain patterns of the temperature structure in the near surface layers of the Gulf, vertical temperature difference charts of the first 30m were constructed. These are shown in Figures 1, 3, 5, and 7. For comparison purposes a historical average temperature difference chart (Figure 9) for the first 100 feet ($\approx$ 30m) was also constructed. A depth of 100 feet was chosen, as the historical mean temperatures for the surface and for 100 feet, were readily available for each one degree quadrangle in the Gulf. These data were the result of an extensive compilation made by Margaret K. Robinson of Scripps Institution of Oceanography.

D. HEAT POTENTIAL COMPUTATION

The heat excess above the 26C isotherm was computed. The choice of a temperature of 26C was made for the following reasons. Hurricanes apparently form only over water whose surface temperature is greater than 26C [Byers, 14; Ramage, 15] and receive little or no energy from the sea if the sea surface temperature falls below this value [Malkus, 1].

The computation involved the simple relationship for heat content:

$$Q = \rho C_p \Delta T \Delta Z$$

where: ρ = density (gm/cm^3)

C_p = specific heat at constant pressure (cal/gm/degree)

ΔT = average temperature (C) difference above 26C for a given depth increment

ΔZ = depth increment [cm].

For each computation the density was taken as 1 gm/cm^3 and although it is generally thought that specific heat increases slightly with salinity and temperature and decreases with increasing pressure [Dietrich, 16] it was taken as 1 cal/cm/C. In each case the depth increment was taken as five meters. This computation was completed for a sufficient number of stations on each cruise to enable contour charts to be made for each year. These charts are shown in Figures 10, 11, 12, and 13.

Since there were a considerable number of heat computations involved, a program was written for use on an IBM 360 computer. A sample program is attached. The computation involves the assumption of a linear temperature profile for each five meter interval. The average temperature difference from 26C, for each five meter interval, is computed. Using this and the linear temperature profile assumption, the problem of computing the heat content then becomes simply one of determining the area of the approximating rectangle. Since most of the profiles did not have 26C exactly at one of the 5m depth increments, the next temperature below 26C was used to complete the profile. The point intercept formula was then used to arrive at the depth of the 26C isotherm and the area of the resulting triangle was computed. The computations were all referenced to a selected volume with unit surface area.

Whitaker [17], in his study of hurricane Betsy (1965), used Simpson's Rule and construction on graph paper to compute the heat content of the water column above 26C. He also assumed a temperature-depth profile composed of linear segments. A computational check of both methods showed a difference in values of less than 3 percent. This general agreement tends to lend credence to both methods of computation.

In most of the cases considered the 26C isotherm was encountered prior to reaching a depth of 125 meters. For ease of computation and to limit unnecessary accuracy, this depth was taken as the maximum depth of consideration. For the few exceptions encountered, approximately five stations per cruise, a check of heat content showed the error to be less than one percent of the total value.

In view of the approximations and assumptions used, the values of heat potential were rounded to the nearest 100 cal/cm^2. Any errors encountered were negligible since contouring intervals of 5,000 cal/cm^2 were used. This interval was sufficient to show the yearly heat content trend.

E. SEA SURFACE TEMPERATURE DECREASE CALCULATIONS

As a final part of the analysis, a few stations for each cruise were selected and a computation was made as to the expected change in the sea surface temperature, should a hurricane spend one-half day or one-full day over the given location. The stations were selected to include locations of maximum, minimum and intermediate potential heat capacity. It was assumed that the rate of heat transfer remained the same throughout the period regardless of the initial temperature difference from 26C. An average rate of heat removal of 4,000 cal/cm^2/day was used.

The figure of 4,000 cal/cm^2/day was chosen as representative of the generally accepted range of 3,000 to 5,000 cal/cm^2/day, values of heat transfer to the area of hurricane force winds. Using the turbulent exchange formulas of Jacobs [18], Malkus and Riehl [19] arrived at a value of 3,140 cal/cm^2/day, for a theoretical model for a moderate hurricane. Leipper [7], using post Hilda data, estimated 4,150 cal/cm^2/day and Whitaker [17], in an analysis of hurricane Betsy, arrived at a figure of 3,750 cal/cm^2/day.

III. ANALYSIS OF RESULTS

A. NEAR SURFACE TEMPERATURE STRUCTURE

1. Cruise 65-A-11

Figure 1, shows the contours of the 0-30m temperature differences from station data for this cruise. The 1C contour has been included for added definition not required for other cruises. The results show an essentially isothermal region in the deep eastern Gulf region, with near zero temperature differences, but with increasing differences as one proceeds east or west of the eastern region. Most of the areas covered by the cruise show differences of 1C or less. Differences exceeding 2C are found some 130 km northwest of Cuba; near 25.5N, 90W; in the northeast Gulf; and along the northern coast. The maximum difference observed was 2.36C and this occurred off the Alabama coast. The range of differences was 3.36C to 0.17C. Since surface temperatures were uniformly high, the large area of differences equal to or less than 2C could indicate that considerable quantities of heat are available there, at least in the upper 30 meters.

The depth of the 22C isotherm is shown in Figure 2, which shows a reasonably well developed eddy detached from the loop current and centered near 24.5N, 87W. The isotherm is found at a maximum depth of approximately 225m. There appears to be a relationship between the 22C isotherm depth and the vertical temperature differences, as might be expected. In the central region of the eddy, where low differences were found, the isotherm occurs at a much greater depth than to the north, along the coast, where the temperature differences were higher.

2. Cruise 66-A-11

The 0-30m vertical temperature difference chart (Figure 3) shows an isothermal area in the deep eastern region which is similar to 1965, however, there are now some significant changes. The computed differences had a much higher range for this year, as is evidenced by the range of contours used (0-10C instead of 0-4C) and the extreme values of 11.6C and 0.1C. An isothermal region now appears to the northwest of Cuba and there are essentially isothermal conditions off the Louisiana coast. In these locations in 1965, differences exceeding 2C were found. To the west of the deep eastern Gulf much higher differences than in 1965 are found. This region of large vertical temperature differences could indicate that low values of heat potential exist there. The large differences off the northern portion of the Yucatan Peninsula can probably be attributed to upwelling of subsurface waters in the area [Perlroth, 8].

The 22C isotherm depth chart (Figure 4) shows the loop current extending to the north and west of its position of 1965. The maximum depth of the isotherm now occurs at approximately 250m. A necking down of the current and then a spreading out to the south is in evidence. It can be seen here, as before, that where the 0-30m vertical temperature differences are small, the 22C isotherm is found at greater depths than where the differences are large. The location of the ridge axis of the major highs in Figure 4 and the trough axis of the major lows of Figure 3 correspond very well.

3. Cruise 67-A-6

The results from this cruise (Figure 5) show major differences from the two previous years. The deep eastern Gulf region now shows a

large vertical temperature difference. It might be expected, then, that this region would be an area exhibiting a low heat content. The largest difference region occurs to the east, near 26N, 85.5W. The previous two years showed some indication of a large difference in this area, but not nearly so well developed. Low differences are present just north of Cuba. This is in sharp contrast to 1965, where differences exceeding 2C were found in the same area. A large area in the northwest portion of the Gulf shows essentially an isothermal condition to 30m. The same area exhibited some differences exceeding 4C in 1965 and 2C in 1966. The total range of differences encountered in 1967 were 9.4C to 0C.

The 22C isotherm chart, Figure 6, indicates the loop current has separated, with a detached eddy located north of the Yucatan Peninsula and the loop in the region west and north of Cuba. The 22C isotherm is found near 200m north of Cuba and near 125m in the northwest portion of the Gulf. These regions are areas of small vertical temperature differences. The indicated region of the 0C contour, north of the Yucatan Peninsula in Figure 5, corresponds in location to the eddy detached from the loop current in Figure 6. In the deep eastern Gulf region the 22C isotherm rises to within 50-75m of the surface.

4. <u>Cruise 68-A-8</u>

The vertical temperature difference chart, Figure 7, shows a return to the near isothermal conditions in much of the deep eastern Gulf region. However, the isothermal region now appears to be wider than, but not to have as great a northern extension as either 1965 or 1966. Further, the area inside the 0C contour lines in the deep eastern Gulf for 1968 exhibited several stations having positive differences, which was not the case for any of the previous three years.

The large temperature difference region seen in the north section is somewhat reminiscent of 1967, but is not seen in either 1965 or 1966. The large difference region in the northeastern portion of the Gulf, which appears to be a general characteristic of all four years, is well defined in 1968. The total range of temperature differences for 1968 was 9.5C to +0.4C.

The 22C isotherm chart, Figure 8, shows a return to a loop current pattern with some similarity to that of 1966. However, the current now appears elongated and does not neck down so severely. Further, the maximum depth of the 22C isotherm occurs near 200m instead of 250m, as in 1966. As before, in the previous four years, the 22C isotherm appears nearer the surface where the 0-30m vertical difference is small.

5. Average Vertical Temperature Differences

The historical average vertical temperature difference chart for the Gulf of Mexico is shown in Figure 9. The 1.5C contour has been included for added definition. In water deeper than 1000m, the averaged picture shows the vertical temperature differences to 100 ft to be generally less than 2C. Water deeper than 1000m covers the predominant area of the Gulf. There is again the large gradient present off the northern tip of the Yucatan Peninsula, probably related to upwelling there. A comparison of this figure with the synoptic data pictures in Figures 1, 3, 5, and 7, shows a significant loss of detail. The averaging process, for changing situations, removes many of the salient features. The result on such an average chart is a representation of a parameter that does not accurately indicate the particular synoptic patterns. The average picture does, however, prove useful in areas where there is insufficient synoptic data available.

Since the synoptic data sets do not cover the whole Gulf region, a complete comparison between the averaged chart and the yearly charts unfortunately cannot be made. However, it is important to emphasize some of the more important features that are found from the analysis of synoptic data and are not found in the averaged data. All the cruises show variances from the historical average, but Cruise 67-A-6, Figure 5, shows the greatest differences. Much higher temperature differences exist throughout the deep eastern Gulf area and in the northeastern portion of the Gulf. There is some similarity in low values north of Cuba. In comparing other cruises with Figure 9, the detail northwest of Cuba in Cruise 65-A-11; the ridge of large differences extending approximately north-south along 90W in Cruise 66-A-11; and the well defined essentially isothermal areas in the deep eastern Gulf in Cruise 68-A-8 are not indicated by the averaged data chart.

B. HURRICANE HEAT POTENTIAL

1. Cruise 65-A-11

The results of the heat potential computations for 1965, shown in Figure 10, indicate an area of heat potential in excess of 15,000 cal/cm^2 which extends generally throughout the deep eastern Gulf region. This area of high potential corresponds to the isothermal region seen in the vertical temperature difference chart of Figure 1. The maximum value of heat potential was approximately 24,700 cal/cm^2. Areas with potentials less than 5,000 cal/cm^2 are few. Some occur along the northern coastline, and others are centered near 27N, 91.5W and 23.5N, 85.5W. The minimum value of heat potential encountered was approximately 1,700 cal/cm^2. The impression is that in this situation a hurricane

could obtain the most heat from the Gulf if it were to pass in a general northwesterly direction through the deep east Gulf region. On the other hand, a northerly route between 91W and 92W could not provide large quantities of ocean energy to a hurricane.

2. Cruise 66-A-11

The 1966 heat potential contours, Figure 11, show a remarkable similarity in appearance to the chart of the depth of the 22C isotherm (Figure 4). The area of high heat potential (above 15,000 cal/cm^2) now extends from just northwest of Cuba toward the Mississippi Delta region and remains above 10,000 cal/cm^2 nearly to the north Gulf coast. The low trough between the two highest heat potential areas is now located some 160 km northwest of its position in 1965. The path of maximum available heat is much the same as for the previous year. The maximum computed heat potential for this year was somewhat higher, approximately 30,200 cal/cm^2. The minimum heat potential, 700 cal/cm^2, occurred just north of the Yucatan Peninsula. This was related to the large vertical temperature differences found there. If the area just north of the Yucatan Peninsula is excluded, the next lowest heat potential, 5,000 cal/cm^2, occurred just south of the Alabama coast, along 87W.

3. Cruise 67-A-6

The results from this cruise (Figure 12) show major differences from the two previous years. One of the first observations is that north of 25.5N there is no contour of heat potential in excess of 15,000 cal/cm^2 and values in the neighborhood of 10,000 cal/cm^2 generally predominate. In both of the previous years, some values in excess of 20,000 cal/cm^2 were found in this area. There does appear a region of high heat potential immediately to the northwest of Cuba. This was

observed in the previous two years in varying patterns. The maximum value of heat potential occurred just north of Cuba and was approximately 25,300 cal/cm^2 and a maximum of 21,000 cal/cm^2 was found in the southwest portion of the deep eastern Gulf region. A minimum value of 4,300 cal/cm^2 occurred just northeast of the Yucatan Peninsula. The northwest Gulf region shows a relatively low heat potential, somewhat similar to both 1965 and 1966.

It is interesting that in general, in the previous two years, a relatively high heat potential was associated with a small vertical temperature difference and a relatively low heat potential was associated with a large vertical temperature difference, while for this year there are two notable exceptions. The northwest Gulf region exhibits a rather low heat potential where an essentially isothermal condition exists (e.g., near 27N, 93W) and heat potentials in excess of 20,000 cal/cm^2 were found in one small area where the vertical temperature difference exceeded four degrees (e.g., near 25N, 88W). The heat potential, of course, depends significantly upon the surface temperature as well as the rate of temperature decrease with depth. The reversal of this correlation in 1967 may be attributed to generally higher water column temperatures when compared to the previous years. As will be seen shortly, 1967 had the lowest maximum value of heat potential.

4. Cruise 68-A-8

Figure 13, the heat potential chart, shows a return to the correspondence between the small vertical temperature differences and high heat potential. A hurricane passing through the Yucatan Peninsula Channel and heading north would find heat potential significantly greater

than 10,000 cal/cm^2 along its path to as far north as 27N. This year had the highest maximum heat potential of all the years investigated, 31,600 cal/cm^2, and this was located almost in the center of the deep eastern Gulf region. The minimum value was 3,600 cal/cm^2.

5. Year to Year Comparison of Heat Potentials

To more clearly emphasize the differences in the hurricane heat potential in the Gulf for the various years it was felt a combined chart of selected contours of heat potential from individual years would be useful. Three such charts are included: one of 5,000 cal/cm^2 contours; one of 20,000 cal/cm^2 contours; and finally one of 15,000 cal/cm^2 contours. These are shown in Figures 14, 15, and 16, respectively. The outer boundary line is included to delineate the average geographical extremity of the collected data stations for the four years.

Figure 14, depicting the 5,000 cal/cm^2 contours for all of the years studied, shows some interesting features. The deep eastern Gulf region was essentially void of low (less than 5,000 cal/cm^2) heat potential for all four years. The northwest portion of the area investigated shows each year a low potential, although it can readily be seen that the size, shape, and exact location changes significantly from year to year. A large area of low heat potential north of the Yucatan Peninsula is seen in 1966 and there is an indication of a similar situation in 1968. Since there is no data available in this area for either 1965 or 1967, no comparison can be made for those years.

The 20,000 cal/cm^2 combined contours, Figure 15, show that, except for one indicated area in the western Gulf region, the areas of high heat potential are confined to a band extending from the northwestern coast of Cuba, northwest to approximately 28N. The change in

size and location from year to year is quite easily seen from the figure. Each year exhibits a maximum near Cuba, with 1965 showing the smallest extent. The shaded areas represent portions where the heat potential was equal to or greater than 20,000 cal/cm^2 for all four years.

Figure 16, perhaps best depicts the significant yearly differences. The 15,000 cal/cm^2 contour was chosen because it seemed to bring out the salient features for the area investigated. The discussion is centered in three regions: Region I, the western area, west of 92W; Region II, the central area, between 90W and 92W; and Region III, the eastern area, east of 90W.

The chart for Region I shows that heat potentials in the 15,000 cal/cm^2 range were found there in all four years. It further shows that they seem to be restricted to water depths greater than 1000m. The yearly movement and definition of the contours is readily apparent from the figure. The year 1966 exhibits the smallest area.

Region II indicates a significant portion where heat potentials of 15,000 cal/cm^2 were found only in 1967 and 1968. The same region in 1965 and 1966 exhibited heat potentials less than or equal to 10,000 cal/cm^2 (Figures 10 and 11). This difference represents approximately one day of energy transfer to a hurricane.

Region III, the largest considered, shows much the same features as Figure 15. The shaded portions represent the areas where heat potential values exceeding 15,000 cal/cm^2 were found in all four years. If a reference point, such as 26N, 87W, is chosen then yearly changes in the location of the high heat potentials can easily be seen. In 1965 the maximum heat potential covers almost the entire region and is not broken by a trough of lower potential until south of 24N and the

corresponding high potential area near Cuba is smaller in extent than the other years. 1966 shows the two areas of high heat potentials to be broken by a trough near 25N and the segment extending north of Cuba has the most northern extent of all the years. The northern segment in 1967 is found further to the southwest and has a much less northern extent than in any previous year. The general pattern exhibited in 1968 is similar to that of 1966, except that the northern segment appears to have been moved generally east and south from the 1966 location.

C. SEA SURFACE TEMPERATURE DECREASE WITH HURRICANE PASSAGE

The results of the computation of possible sea surface temperature decrease with hurricane passage are shown in Appendix A. Calculations are based on an assumed average constant rate of heat transfer, to a hurricane, of 4,000 $cal/cm^2/day$, regardless of the initial sea surface temperature. Three stations for each cruise were selected as generally representative of low, medium and high heat potential areas. The cruise is specified in column one. Column two indicates the geographical positions of the stations and column three lists the hurricane heat potential for each station. The last three columns give, respectively, the initial sea surface temperature; the first-half day sea surface temperature decrease ($\Delta T1$) and the second-half day decrease ($\Delta T2$) associated with a hurricane passage.

Figure 17, shows a schematic plot of the vertical temperature distributions, for two stations on Cruise 68-A-8, #1 and #3, from bathythermograph data. It is included to indicate typical relationships between the vertical temperature structure and the available heat potential in the water columns. The computed value of the heat potential

for each station is indicated in the figure. Station #1 is representative of the "left-hand" water and station #3 is representative of the "right-hand" water of the Gulf loop current, as defined by Leipper [20].

These results bring out two important facts. First, in every case, except 68-A-8 #2 and 3, the sea surface temperature decrease was higher during the first-half day of hurricane passage than during the second-half day. The seemingly anomalous behavior of station #2, where the second-half day temperature decrease exceeded the first-half day temperature decrease, is the result of a sea temperature inversion of approximately 0.3C which occurred between 10 and 15 meters and extended to over 30m in depth. Station 68-A-8 #3 exhibited a temperature difference of only 0.2C in the first 50 meters. This isothermal condition accounts for the sea surface temperature decreases being the same for both the first-half and second-half days. Secondly, the magnitude of the sea surface temperature decrease increases as the available hurricane heat potential decreases. This is generally to be expected since the stations with low heat potentials had, in every case, presented a much more rapid temperature decrease with depth than those stations with high heat potentials and thus could support a hurricane for only a shorter period of time. The sea surface temperature decrease resulting from the removal of an additional 4,000 cal/cm^2 was computed for station 66-A-11 #3. The result was 0.5C which corresponds to a final surface temperature of 28.1C at the end of a second day.

It does appear then, as would be expected, that the smaller the vertical temperature gradient the slower the sea surface temperature would drop when a passing hurricane extracted the assumed 4,000 calories per day. The more slowly the sea surface cools from its initial

temperature the higher the flux into the hurricane in the form of sensible and latent heat.

IV. CONCLUSIONS

The conclusions to be reached are those based on the examination of recurring data for particular months in particular years in the Gulf of Mexico. Were the synoptic data for other areas available, perhaps significant yearly variability would also be obtained.

The results of this research show, for the particular portion of the Gulf of Mexico investigated, that:

(1) Heat available per cm^2 in the Gulf varies with location from approximately 700 to 31,600 calories, when the heat content of water at 26C is taken as zero.

(2) There is a large variance in the size, shape and exact location of both high and low heat potential centers for all four years.

(3) High heat potentials in excess of 20,000 cal/cm^2 are confined to a band extending from the northwestern coast of Cuba, northwest to approximately 28N, for all four years.

(4) The deep eastern Gulf region was essentially void of heat potentials less than 5,000 cal/cm^2 for all four years.

(5) Low heat potentials in the 5,000 cal/cm^2 range are prevalent in the Gulf north of approximately 27.5N for all four years and extending north of the Yucatan Peninsula for 1966 and 1968.

(6) The 0-30m vertical temperature difference patterns vary considerably from year to year and from the historical average condition. Differences as great as 11.6C and as low as 0C were observed.

(7) The topographies of the 22C isothermal surfaces are significant in heat potential computations. High values of heat potential are

found where the 22C isotherm is deep and low values of heat potential are found where the 22C isotherm is near the surface.

(8) The calculated sea surface temperature decrease associated with hurricane passage is usually greater during the first-half day than the second-half day and that the magnitude of the sea surface temperature decrease increases as the available hurricane heat potential decreases.

(9) The study of the amount and the distribution vertically of heat may provide a good clue to changes in intensity and tracking of hurricanes.

V. RECOMMENDATIONS

The most important recommendation that can be made as a result of this research is that further study, similar to this, must be conducted in order to attempt a correlation between the amount and vertical distribution of heat to changes in the intensity and tracking of hurricanes. At the present time little is known about these subjects. The tracks and intensities of actual hurricanes that occurred subsequent to the August periods of 1965 through 1968 should be compared with the apparent heat availability as a first step in this correlation.

The importance of synoptic observations in an analysis of the available heat per cm^2 in an area cannot be over-emphasized. This applies equally well to any investigation of a parameter with the goal of describing its synoptic pattern. For changing situations, results obtained from historical averaging should give way to recurring synoptic observations whenever possible.

The results indicate that to assume the ocean as having a constant temperature structure, both in the horizontal and vertical, is not realistic and that mathematical models of hurricanes should include the near surface temperature structure as a variable.

APPENDIX A

COMPUTED SEA SURFACE TEMPERATURE DECREASE UNDER HURRICANE INFLUENCE

Cruise	Station Location	Hurricane Heat Potential (cal/cm^2)	Initial Sea Surface Temp. (C)	ΔT_1 (C)	ΔT_2 (C)
65-A-11	#1 23-23N 85-27W	4,100	28.5	1.6	0.9
	2 26-14N 89-33W	12,000	29.1	0.8	0.5
	3 25-19N 86-02W	25,700	29.6	0.5	0.4
66-A-11	#1 24-27N 87-50W	3,600	27.9	1.2	0.8
	2 25-23N 86-17W	9,600	29.0	0.8	0.7
	3 26-16N 88-07W	30,200	29.4	0.5	0.3
67-A-6	#1 27-23N 87-10W	6,500	30.1	2.1	1.0
	2 26-14N 89-03W	14,000	29.4	0.8	0.5
	3 25-13N 86-58W	21,000	30.3	0.8	0.5
68-A-8	#1 26-47N 89-26W	4,800	28.7	1.3	1.0
	2 27-01N 87-47W	17,000	29.8	0.4	0.6
	3 25-26N 86-49W	31,600	30.2	0.4	0.4

ΔT_1 - Sea surface temperature decrease (C) in the first-half day (2,000 cal/cm^2 removed).

ΔT_2 - Sea surface temperature decrease (C) in the second-half day (an additional 2,000 cal/cm^2 removed).

```
C     A.   TITLE: OCEAN HEAT POTENTIAL COMPUTATIONS FOR
C                 CRUISE 65-A-11
C
C     B.   PURPOSE: TO COMPUTE THE EXCESS OCEAN HEAT CONTENT
C                   OVER THAT CONTAINED IN 26C WATER.
C
C     C.   ARGUMENTS:
C          A-     TEMPERATURE DEGREES C
C          B-     AVERAGE TEMPERATURE OVER 5 METER INTERVAL
C          CP-    SPECIFIC HEAT AT CONSTANT PRESSURE, TAKEN AS
C                 1.0 CAL/GM-DEG
C          N-     NUMBER OF STATIONS
C          NP-    NUMBER OF POINTS PER STATION
C          NS-    STATION NUMBER
C          QI-    INCREMENTAL HEAT CAL/CN2
C          Q-     TOTAL HEAT CAL/CM2
C          RHO-   DENSITY, TAKEN AS 1.0 GM/CM3
C          ZI-    5 METER DEPTH INTERVAL IN CM
C          Z-     SEQUENTIAL 5 METER DEPTH INTERVALS
C          Z1-    DEPTH OF INTERCEPT OF LINEAR TEMPERATURE
C                 APPROX. WITH THE 26 DEGREE ISOTHERM
C
      DIMENSION A(50), Z(50), QI(50), NP(200)
      N=152
      READ (5,100) (NP(I),I=1,N)
      WRITE (6,200) N
      ZI=500.0
      DO 11 I=1,30
      V=I-1
      Z(I)=V*ZI
   11 CONTINUE
      DO 12 I=1,N
      NN=NP(I)
      WRITE (6,220) I,NN
      READ (5,101) NS,(A(J),J=1,NN)
      WRITE (6,204) NS,(A(J),J=1,NN)
      DO 14 J=1,NN
      A(J)=A(J)-26.0
   14 CONTINUE
      Q=0.0
      CP=1.0
      RHO=1.0
      NA=NN-1
      DO 13 J=1,NA
      IF (A(J+1).LT.0.0) GO TO 20
      B=(A(J)+A(J+1))/2.0
      QI(J)=RHO*CP*B*ZI
      GO TO 18
   20 Z1=Z(J) + ZI*(A(J))/(A(J)-A(J+1))
      QI(J)=RHO*CP*0.5*(Z1-Z(J))*A(J)
      Q=Q+QI(J)
      WRITE (6,206) Z1,QI(J),Q
      GO TO 13
   18 Q=Q+QI(J)
      WRITE (6,208) Z(J),QI(J),Q
   13 CONTINUE
   12 CONTINUE
  100 FORMAT (40I2)
  101 FORMAT (I3,25F3.1)
  200 FORMAT('1',6X,'CRUISE 65-A-11, NUMBER OF STATIONS:'
     15X,'N =',I5//)
  204 FORMAT ('0',5X,I3,3X,20F5.1//11X,5F5.1/)
  206 FORMAT (5X,3F12.2//)
  208 FORMAT (5X,3F12.2)
  220 FORMAT ('0',10X,2I5)
      STOP
      END
```

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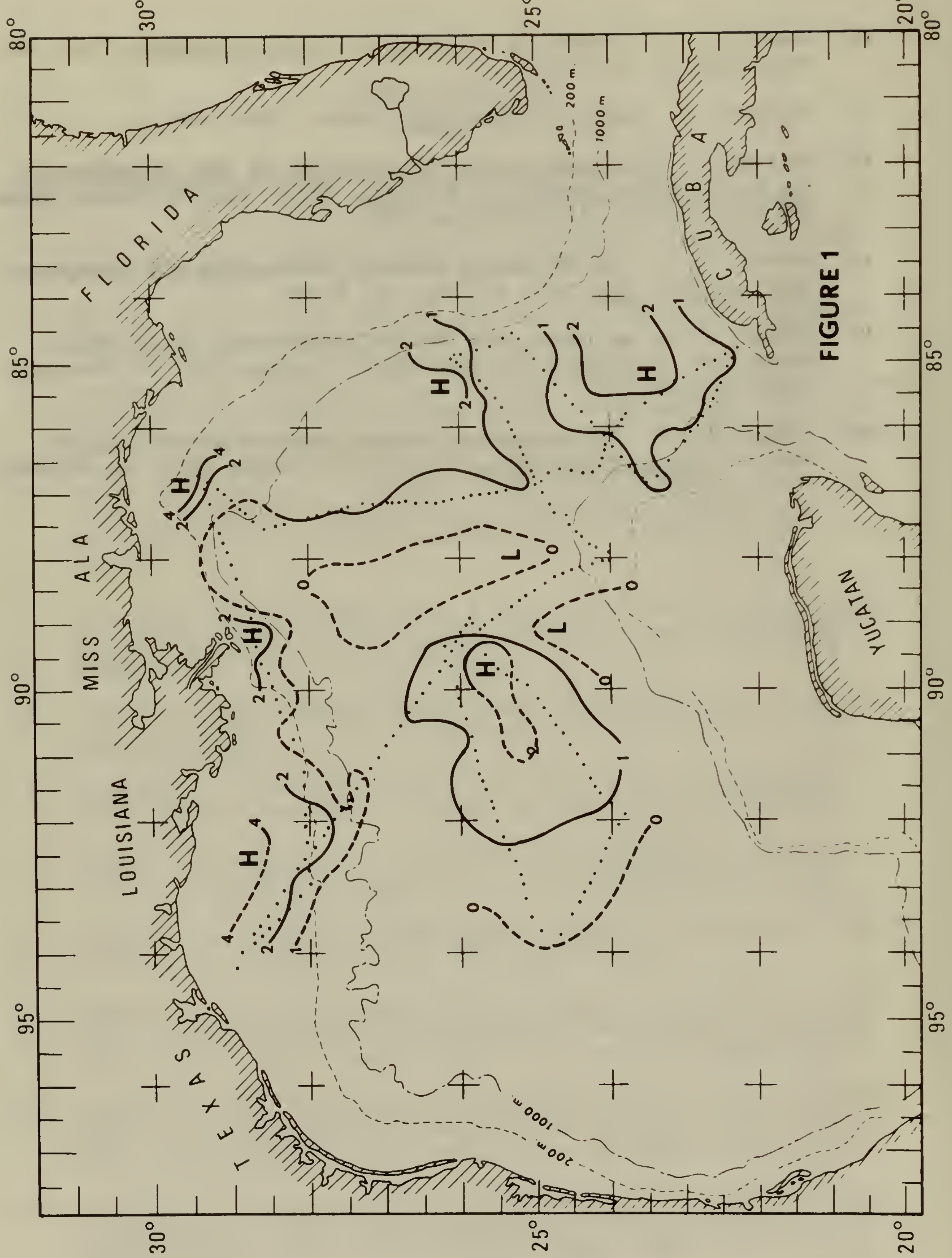

Figure 1. 0-30m Vertical Sea Temperature Differences (C) for Cruise 65-A-11, 10-24 August 1965.

Figure 2. Topography of the 22C Isothermal Surface (in meters) for Cruise 65-A-11, 10-24 August 1965 (after Leipper).

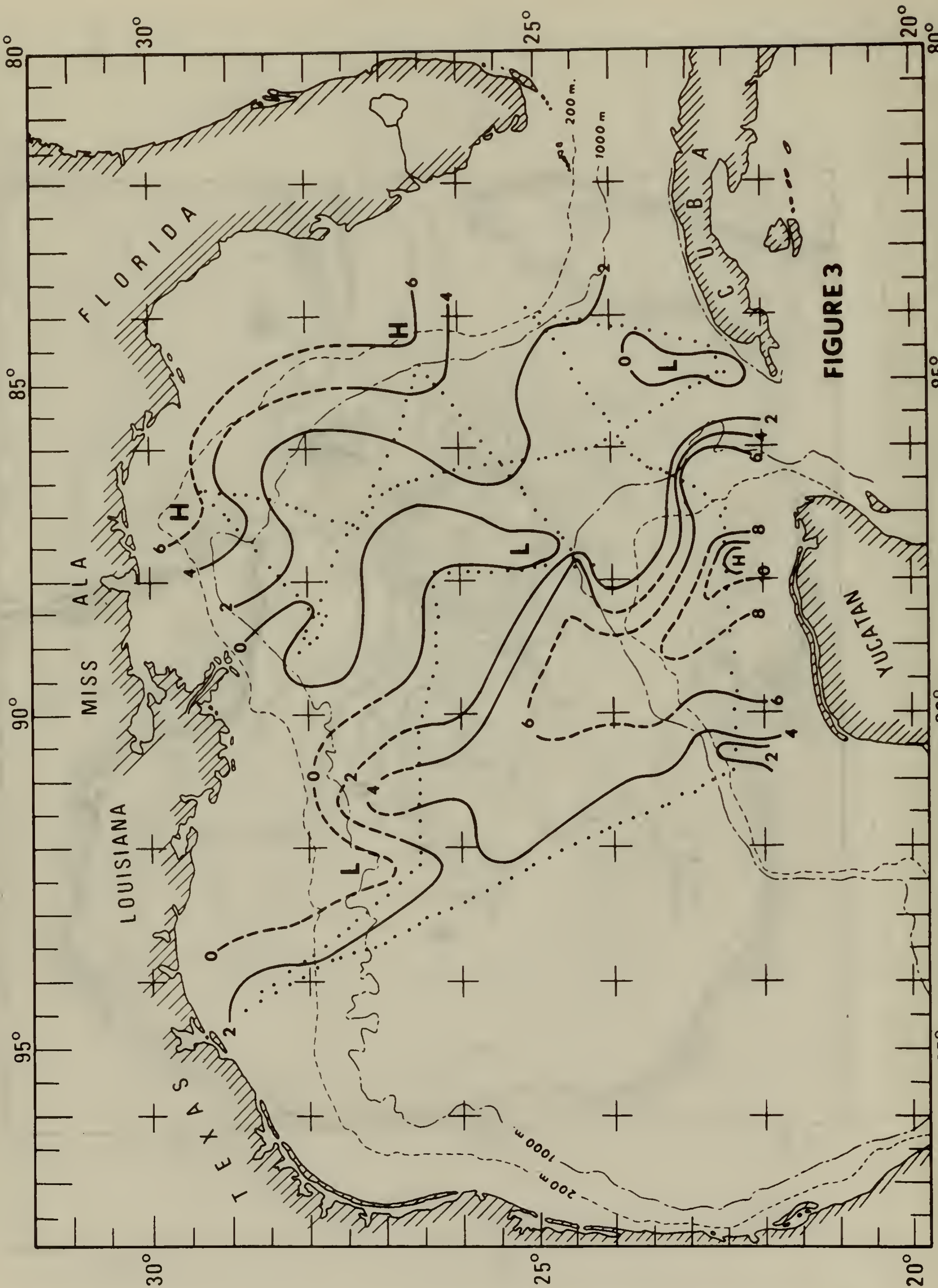

Figure 3. 0-30m Vertical Sea Temperature Differences (C) for Cruise 66-A-11, 4-18 August 1966.

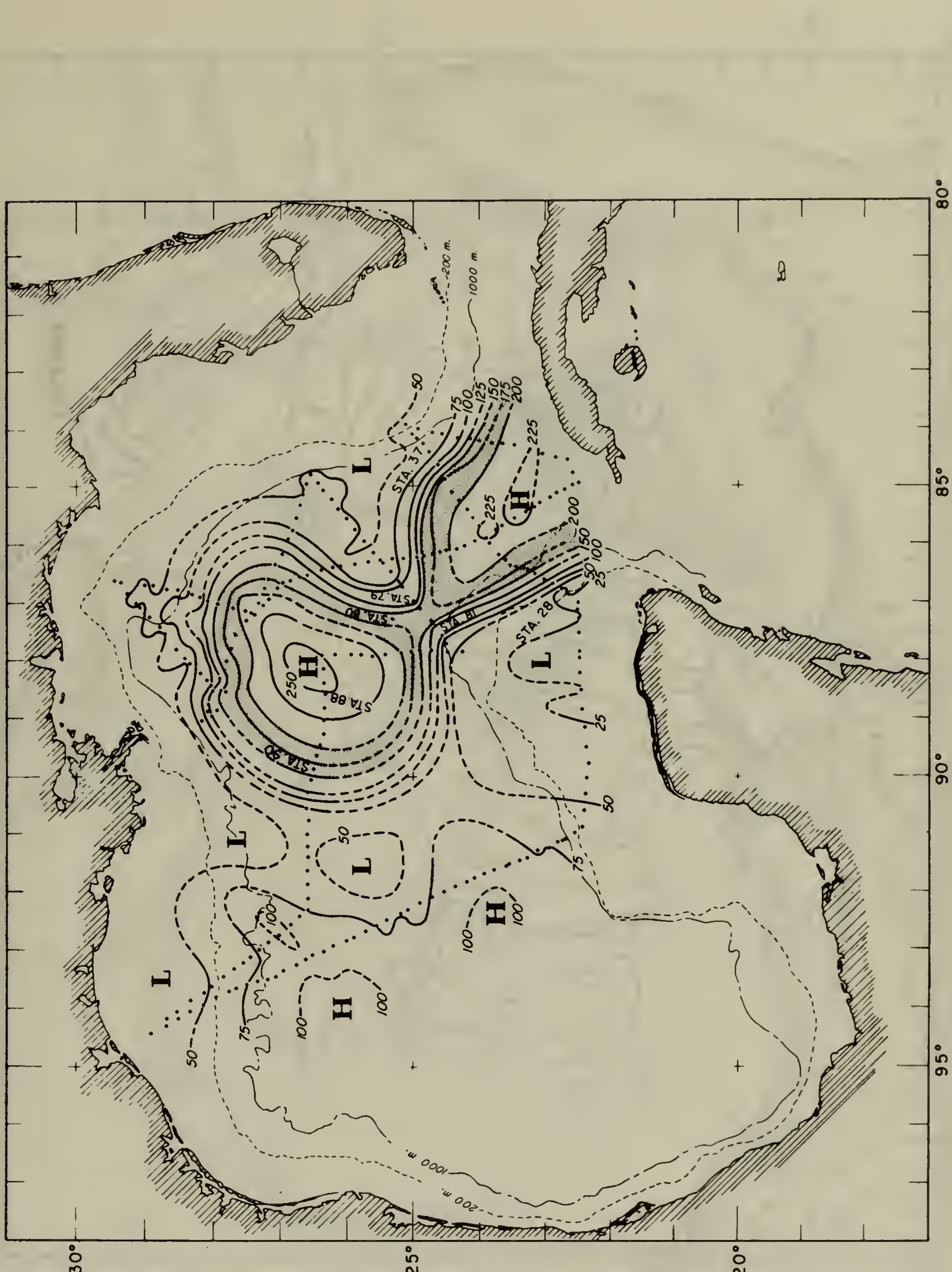

Figure 4. Topography of the 22C Isothermal Surface (in meters) for Cruise 66-A-11, 4-18 August 1966 (after Leipper).

Figure 5. 0-30m Vertical Sea Temperature Differences (C) for Cruise 67-A-6, 4-22 August 1967.

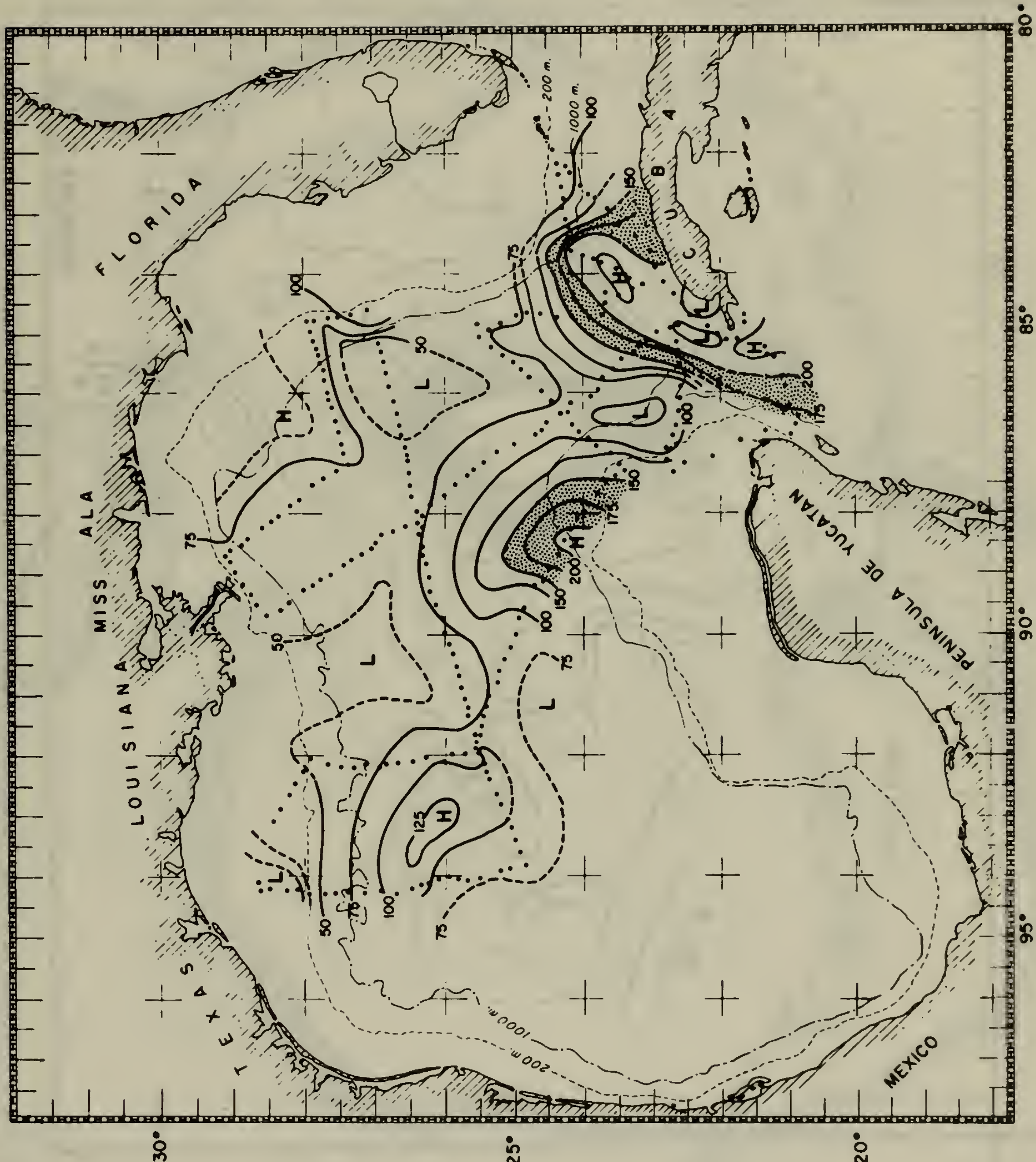

Figure 6. Topography of the 22C Isothermal Surface (in meters) for Cruise 67-A-6, 4-22 August 1967 (after Leipper).

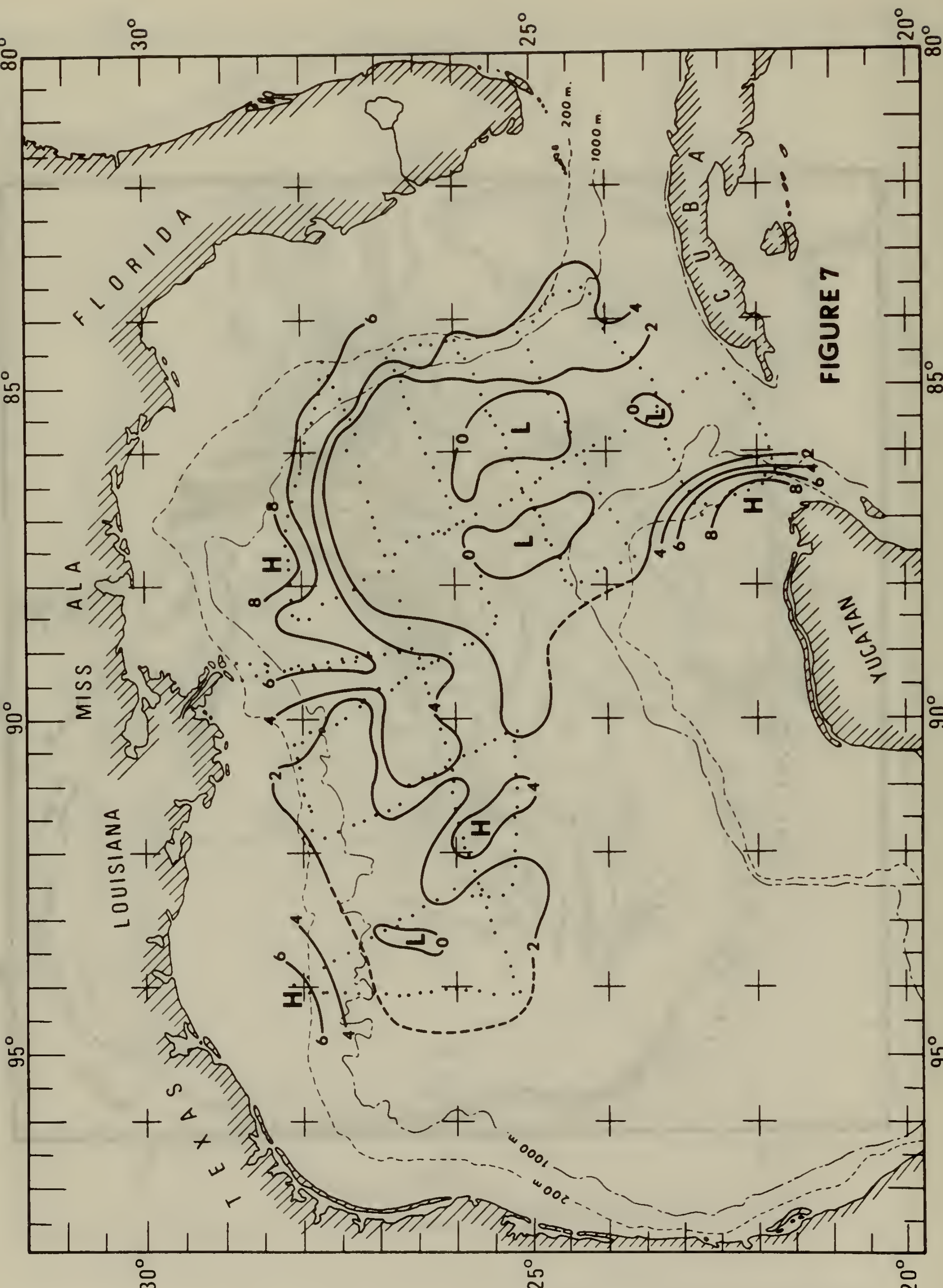

Figure 7. 0-30m Vertical Sea Temperature Differences (C) for Cruise 68-A-8, 17 August-5 September 1968.

Figure 8. Topography of the 22C Isothermal Surface (in meters) for Cruise 68-A-8, 17 August-5 September 1968 (after Schneider).

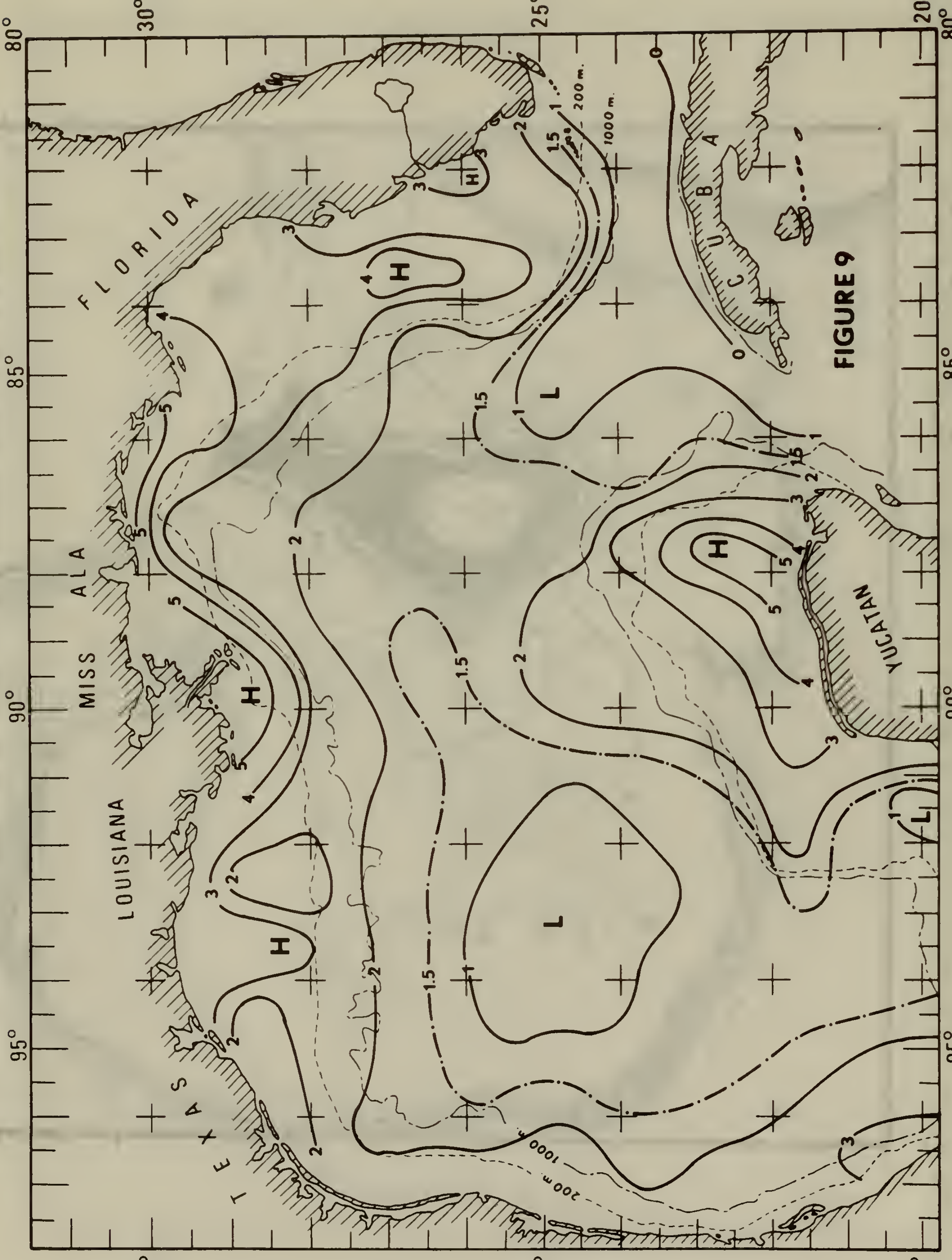

Figure 9. Historical Average 0-100 ft Vertical Sea Temperature Differences (C).

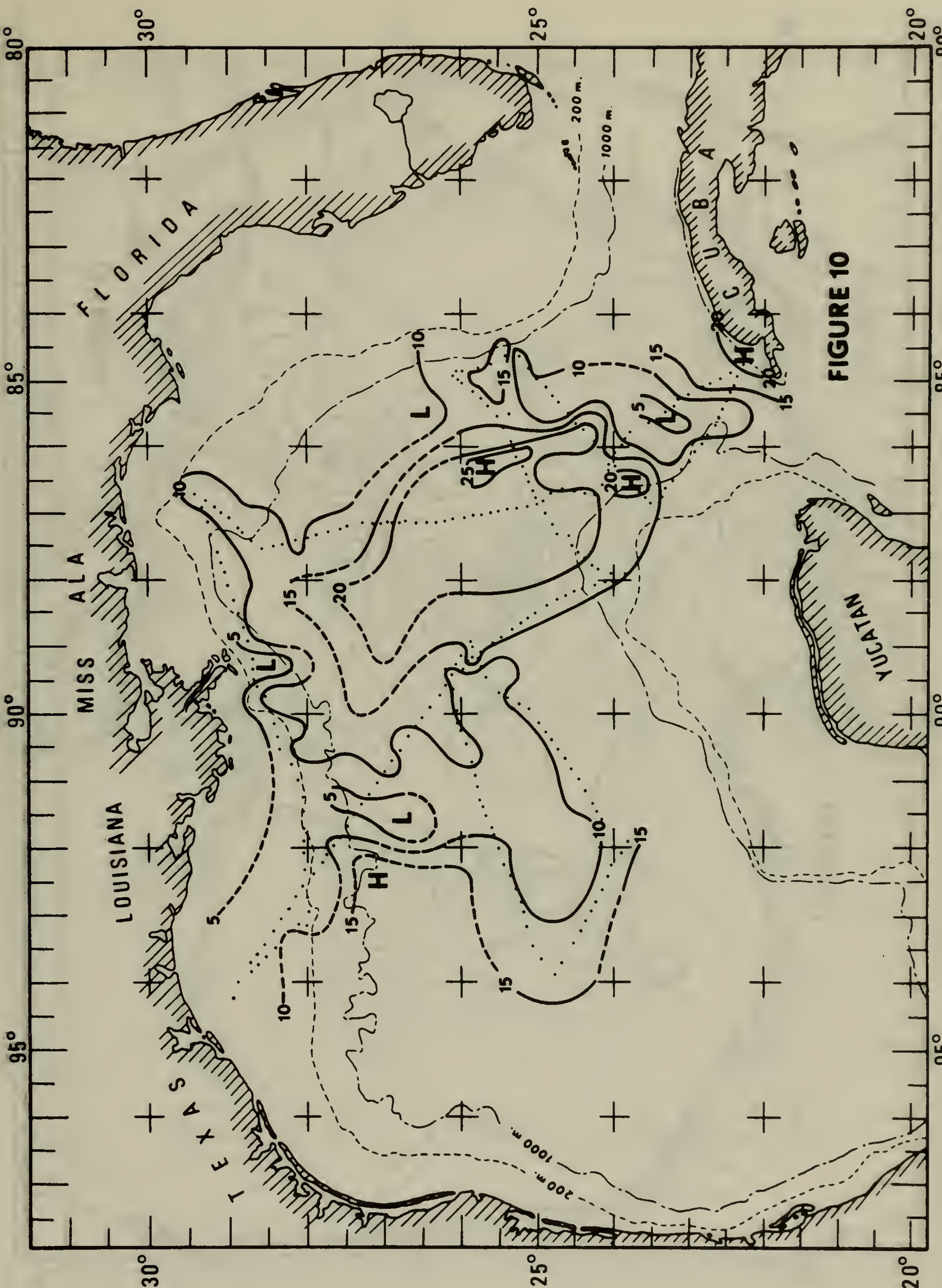

Figure 10. Ocean Hurricane Heat Potential (10^3 cal/cm^2) for Cruise 65-A-11, 10-24 August 1965.

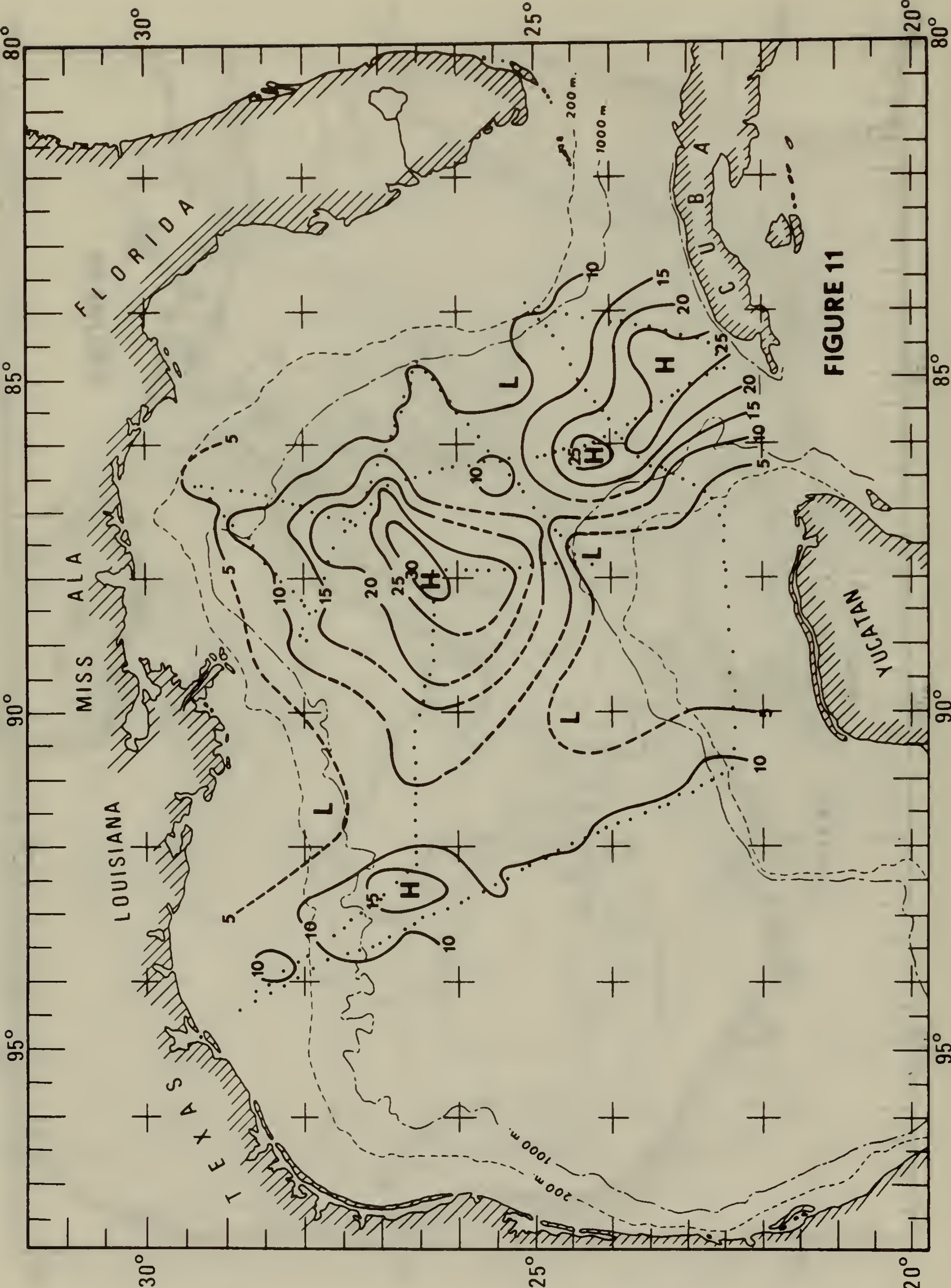

Figure 11. Ocean Hurricane Heat Potential (10^3 cal/cm^2) for Cruise 66-A-11, 4-18 August 1966.

Figure 12. Ocean Hurricane Heat Potential (10^3 cal/cm^2) for Cruise 67-A-6, 4-22 August 1967.

Figure 13. Ocean Hurricane Heat Potential (10^3 cal/cm^2) for Cruise 68-A-8, 17 August-5 September 1968.

Figure 14. Combined 5,000 cal/cm^2 Ocean Heat Contours for all August Cruises in the Period 1965-1968.

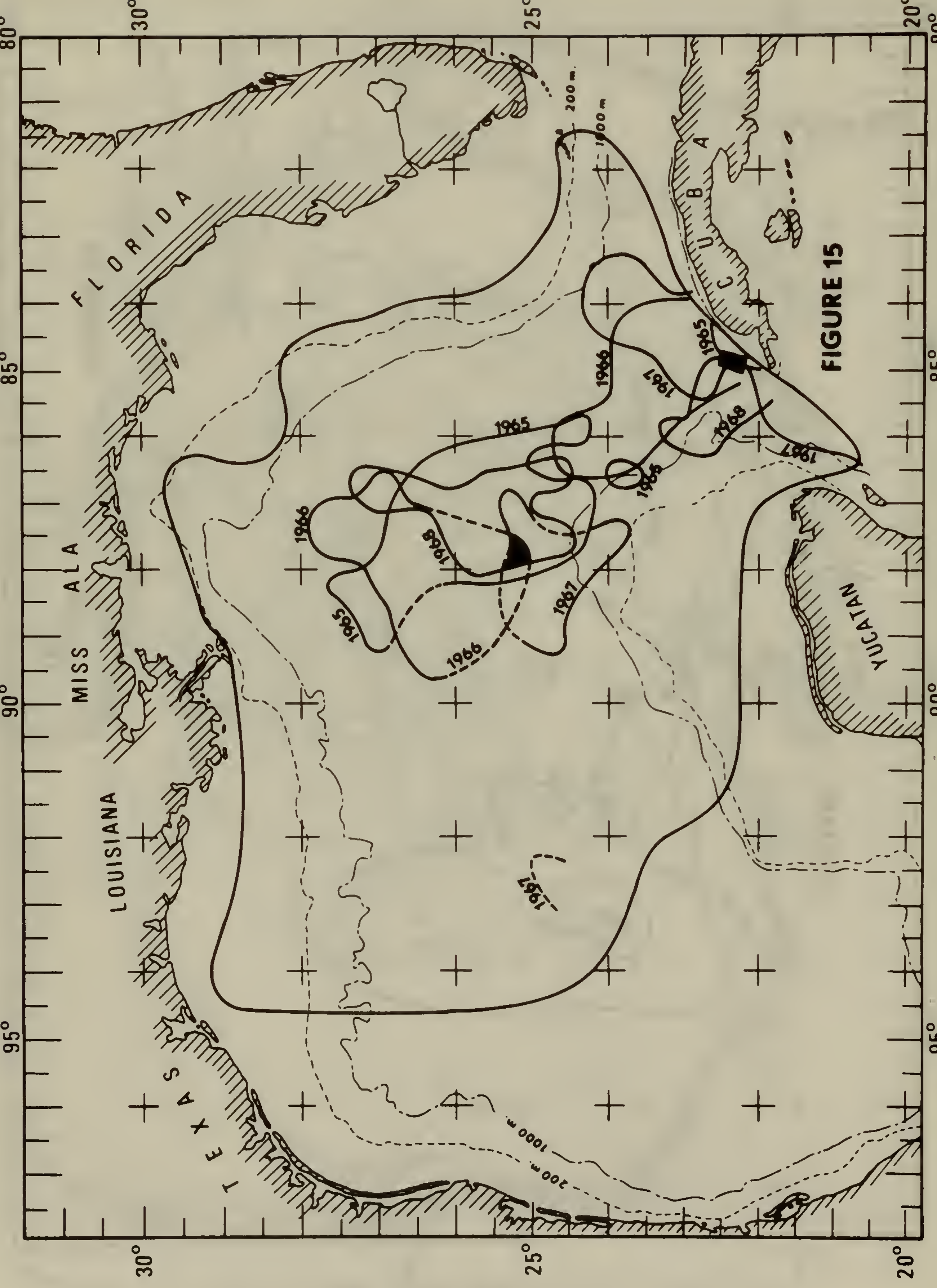

Figure 15. Combined 20,000 cal/cm^2 Ocean Heat Contours for all August Cruises in the Period 1965-1968.

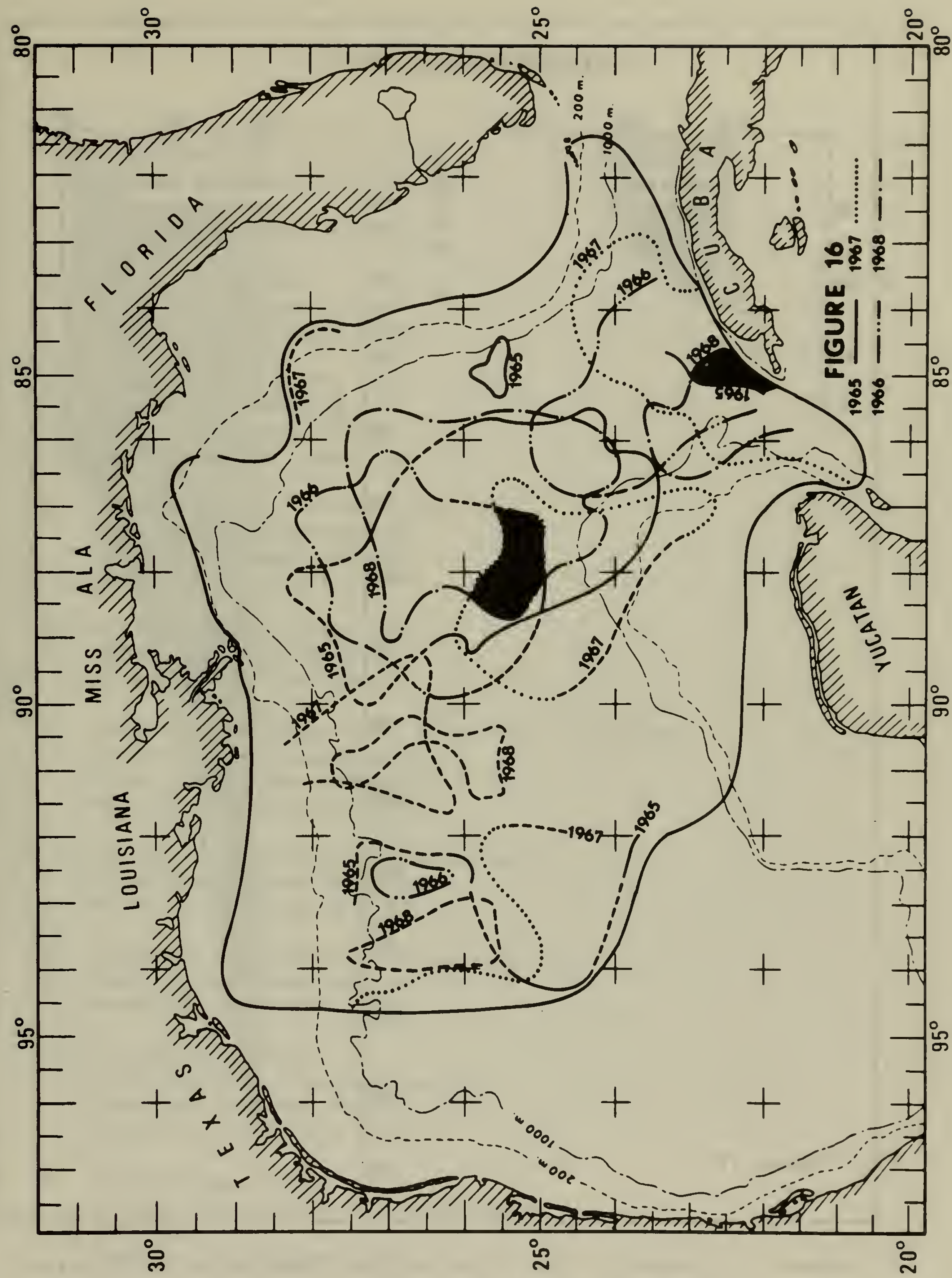

Figure 16. Combined 15,000 cal/cm^2 Ocean Heat Contours for all August Cruises in the Period 1965-1968.

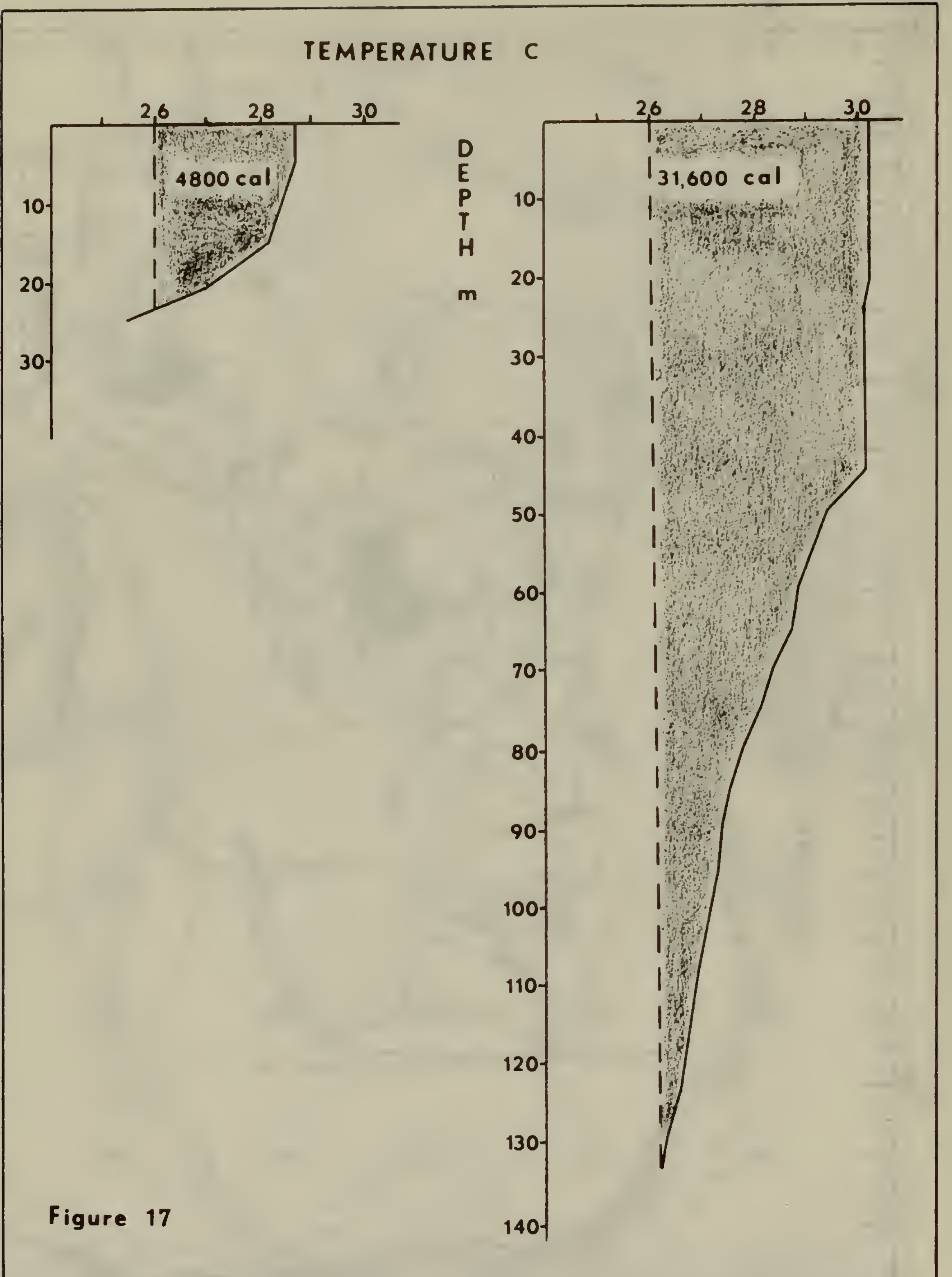

Figure 17. Schematic Plot of the Vertical Temperature Distributions for Station 68-A-8 #1 and 3.

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13. ABSTRACT

An analysis of the "hurricane heat potential" of the Gulf of Mexico early in the hurricane seasons for the individual years 1965 to 1968 was conducted. Results show that if the heat content of water at 26C is taken as zero, then the amount of heat available per cm^2 in the Gulf varies from approximately 700 to 31,600 calories. The areas of high heat content are found to vary yearly. Further, since the sea surface temperature decrease during a storm depends upon the near surface vertical temperature gradient, the temperature differences between the surface and 30m depth were also studied. Vertical temperature differences were found to vary from 0C to 11.6C, depending upon location. Computations based on ranges of heat content and vertical temperature structure showed that a passing hurricane with an assumed flux from the sea of 4,000 cal/cm^2/day would cause the sea surface temperature to decrease some 3.1C per day in some regions but only 0.8C in others.

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